AGU PUBLICATIONS

Tectonics

RESEARCH ARTICLE
10.1002/2017TC004627

Special Section:
Orogenic cycles: from field observations to global geodynamics

Key Points:
- A review of Internal and External Ligurian Units (Northern Apennines) allows revisiting subduction initiation and precollision history
- The debris deposits in Ligurian Units suggest building of a double-vergent orogen (the historic “Ruga del Bracco”) at 80 Ma before collision
- Subduction inception in the Adria Ocean-Continent Transition suggested by composition of the debris and their tectonometamorphic history is explained

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Citation:
Marroni, M., Meneghini, F., & Pandolfi, L. (2017). A revised subduction inception model to explain the Late Cretaceous, double-vergent orogen in the precollisional western Tethys: Evidence from the Northern Apennines. *Tectonics*, *36*. https://doi.org/10.1002/2017TC004627

Received 18 APR 2017
Accepted 25 SEP 2017
Accepted article online 4 OCT 2017

A Revised Subduction Inception Model to Explain the Late Cretaceous, Double-Vergent Orogen in the Precollisional Western Tethys: Evidence From the Northern Apennines

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Abstract The Meso-Cenozoic alpine belts of the Mediterranean area are characterized by complex architectures, result of a complex subduction and collision evolution that preserve also a legacy of the rifting-related configuration of the continental margins. The Northern Apennines is a segment of these belts originated during closure of the Ligure-Piemontese ocean and collision between the Europe and Adria plates. The different configuration of the Adria and Europe margins, inherited from asymmetric rifting, is recorded in the Ligurian Units that preserve incorporation into the subduction factory of fragments of the oceanic domain (Internal Ligurian Units) and portions of the Ocean-Continent Transition Zone (OCTZ) toward Adria (External Ligurian Units). We provide here unpublished data on the stratigraphy and sedimentology of these units, together with a review of what is already established in literature. Both data sets combined testify that at 80 Ma, an accretionary prism was growing between the deposition basins of the two groups of units and fed both basins with clasts from the ocean realm, the continental crust, and the subcontinental mantle. We propose that closure of the Ligure-Piemontese ocean occurred through subduction that nucleated at the transition from the oceanic plate and the thinned Adria margin and developed a double-vergent prism by accreting oceanic material and continental extensional allochthons from the OCTZ. We believe the revised site of subduction initiation, and the precollisional architecture, inherited from the rifting and spreading phases, allows reconciling most of the discrepancies between the various interpretations proposed in literature for the precollisional evolution of the Apennines.

1. Introduction

It is widely demonstrated how orogenic processes can be strongly controlled by inherited structures. The paleogeography of the converging margins, and the tectonic processes responsible for their configuration, influence variably (i) the location of subduction initiation; (ii) the distribution of deformation between upper and lower plate; (iii) the shape of the accretionary prism and of the subsequent orogeny, through controlling the development of single or doubly vergent orogens, and, as a corollary; and (iv) the modality of exhumation of metamorphosed units. In addition, there is an ever increasing number of contributions in literature testifying how large portions of the orogen were built well before continental collision, through a series of superimposed tectonic events that can date back to the original rift stage preceding convergence (Beltrando et al., 2010; Cowgill et al., 2016; Fergusson et al., 2016; Malavieille et al., 2016; Zanchetta et al., 2012). The identification and characterization of the precollisional structures is a crucial step for a full understanding of how collisional belts develop.

The “Alpine age” collisional belts of the Mediterranean area (Figure 1) are characterized by complex architectures derived from the overlapping of several deformation events related to a long, multiphase history. This evolution not only comprises the collision of continental margins but can be regarded as a heritage of both the rifting-related configuration of the continental margins and the subduction-related structures (Chenin et al., 2017; Malavieille et al., 2016; Peacock et al., 2016; Vacherat et al., 2014). The Northern Apennines is a segment of the Mediterranean collisional belts that originated from the Late Cretaceous-middle Eocene closure the northern branch of the western Tethys, namely, the Ligure-Piemontese ocean and the subsequent late Eocene-early Oligocene continental collision between the Europe and Adria plates (e.g., Bortolotti et al., 1990; Elter & Pertusati, 1973; Malusà et al., 2009; Marroni et al, 2010; Molli & Malavieille, 2011). In particular, the northernmost sector of the Apennines and the junction area with the Western Alps (Figure 1) record a nearly 90 Ma history that can be now

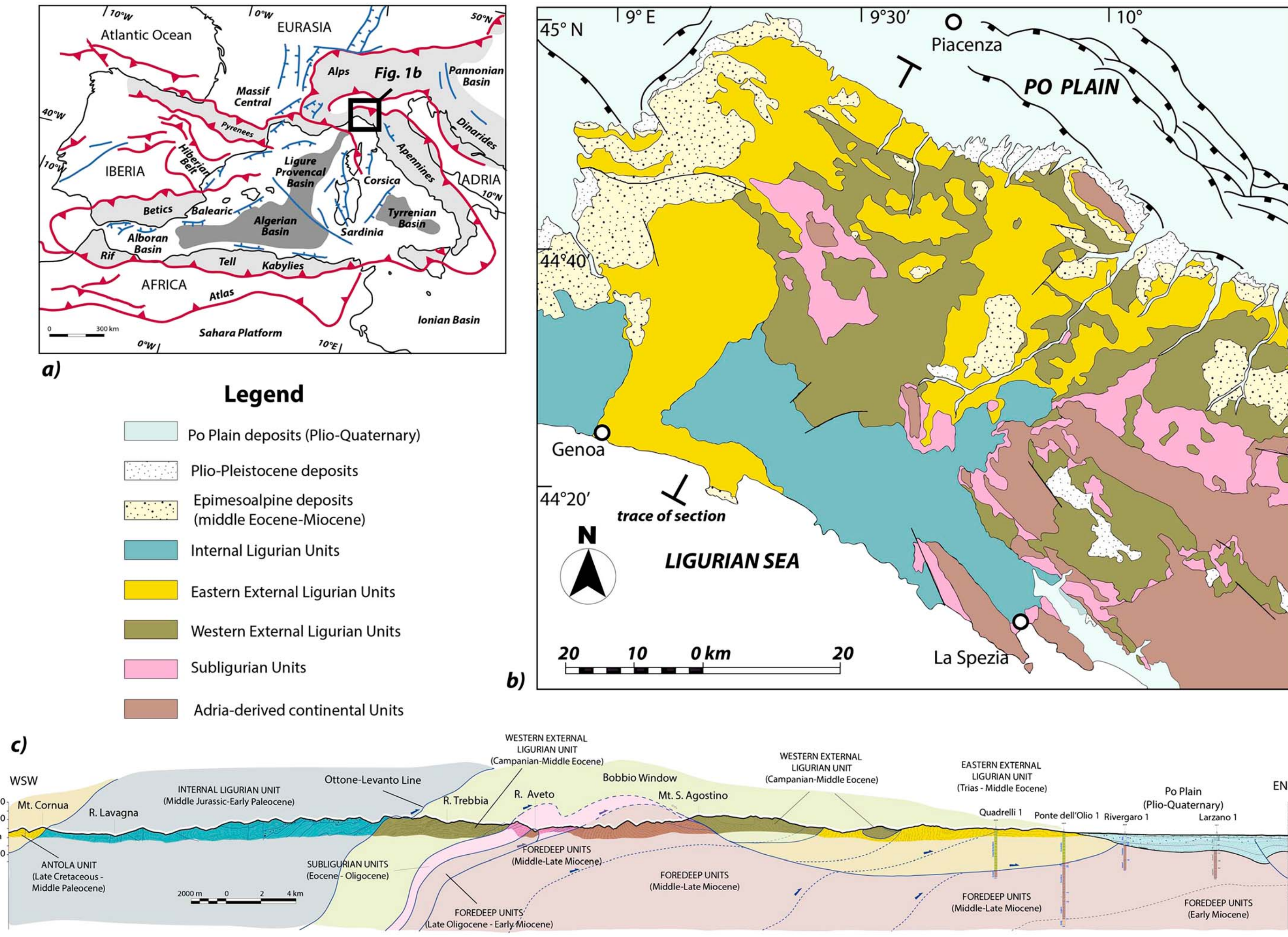

Figure 1. Introduction to the Northern Apennines belt. (a) Overview of the collisional belts (red lines) surrounding the Mediterranean sea (barbed blue lines bound extensional basins). (b) Tectonic sketch map of the Northern Apennines with the main tectonostratigrahic groups of units representative of different paleogeographic domains. Location of map shown in Figure 1a. (c) Regional cross section through the Ligurian Northern Apennines showing the main relationships between the different tectonostratigraphic units. Average trace line of section is indicated in Figure 1b.

deciphered in the complex structural architecture (Molli et al., 2010; Molli & Malavieille, 2011). To explain the structural evolution of this area, many contrasting reconstruction have been proposed (Alvarez et al., 1974; Boccaletti et al., 1971; Bortolotti et al., 1990; Carminati et al., 2004; Elter & Pertusati, 1973; Malusà et al., 2016; Marroni et al., 2010; Marroni & Treves, 1998; Molli, 2008; Molli & Malavieille, 2011; Principi & Treves, 1984; Treves, 1984): main differences between interpretations concern essentially with the dipping of the subduction plane, the time of activity of the two oppositely dipping subductions and the existence of oblique convergence. Despite often strikingly different interpretations, there is growing evidence supporting an evolution through two, diachronous oppositely dipping subductions: a Late Cretaceous-middle Eocene east dipping oceanic and then continental "Alpine" subduction, and a late Eocene to present west dipping "Apennines" subduction (e.g., Boccaletti et al., 1971; Doglioni, 1991; Elter & Pertusati, 1973; Marroni et al., 2010; Molli & Malavieille, 2011).

Some contributions on the tectonic history of the Northern Apennines have also highlighted the occurrence of precollisional and/or preconvergence structures and proposed hypotheses about their impact on the subsequent sedimentation and tectonics. In particular, and as described in more detail in the next section, the need for a deformed structural element located in the northern branch of the western Tethys basin, and representing the embryonic stage of the Northern Apennines edifice, dates back to preplate tectonics times. In 1965, Elter and Raggi depicted and described the "Bracco ridge," a topographic structure of deformed ophiolitic rocks separating two different realms in the Ligure-Piemontese oceanic basin (see also Elter, 1993; Marroni et al., 2001) and influencing the following evolution of the Ligurian domain. The advent of the plate tectonic theory has allowed a better understanding of the paleogeographic and tectonic configuration of the Ligurian branch of the Tethyan basin and the continental margins involved in convergence, as well as suggesting the possible tectonic meaning of the Bracco ridge. Treves (1984) was the first to propose the Bracco ridge as the accretionary wedge built during the Apennine subduction. Subsequently, an evolution through subduction and closure of the Ligure-Piemontese oceanic basin, and building of an accretionary wedge, has been reproposed in several, often deeply contrasting, reconstructions (Argnani, 2012; Festa et al., 2013; Hoogerduijn Strating, 1994; Malavieille et al., 2016; Marroni, 1991; Marroni et al., 2010, 1998; Meneghini et al., 2007; Molli & Malavieille, 2011; Remitti et al., 2007; Vannucchi et al., 2008 and many others). Most of the debate along these different models has been focused on the dipping of the subduction plane, and, for the Ligurian sector of the Northern Apennines, its belonging to the Alpine of Apennine geologic evolution, so that details like the structural features of the wedge prior to collision, that is, the occurrence of single versus double vergence, the Early versus Late Cretaceous time of formation, the exact location of subduction initiation were only partially treated and not reconciled in an unambiguous, universally accepted configuration of the precollisional Apenninic structure and its relationships with the architecture inherited from the rifting and the subsequent oceanic opening. For example, the accretionary wedge prior to continental collision has been drawn as a double-vergent prism in some of the most recent review papers on the evolution of the Northern Apennines (Malavieille et al., 2016; Marroni et al., 2010; Molli & Malavieille, 2011) but none of them focused on presenting detailed structural of stratigraphical evidence supporting a precollisional formation of a retrobelt as developed as the forebelt. As for the initiation of subduction, it is typically considered as having developed in an intraoceanic area (e.g., Argnani, 2012; Boccaletti et al., 1971; Elter & Pertusati, 1973; Schmid et al., 2017; Treves, 1984).

According to the wealth of geological data now available for the Northern Apennines, the aim of this paper is (1) to review all the stratigraphic, structural, and geochemical published data on the Ligurian Units and the existing reconstructions of the precollisional Apenninic structure developed during Late Cretaceous; (2) to provide new, unpublished sedimentological and stratigraphic data on some portions of the Ligurian Units, collected in several years of mapping projects, and combine them with the reviewed data, to propose a novel interpretation on the Northern Apennines tectonics that focuses on the time span ranging from the late stages of rifting to the Late Cretaceous subduction; and, finally, (3) to outline how the precollisional orogeny was influenced by the rifting-related structures.

After a brief introduction to the geological setting and tectonic history, we present in detail the geostructural evidence, by combining unpublished, new data with preexisting work from literature that can be used to support a model of subduction initiation controlled by the rifting and spreading phases and the development of a bivergent belt since the Campanian. We therefore suggest that much of the actual configuration of this orogenic belt developed well before the collisional events.

2. Northern Apennines Tectonic History

The Northern Apennines (Figure 1) is a collisional belt with a long-lived geodynamic history that comprises two diachronous and oppositely dipping subductions and can be summarized through the following main steps (Malavieille et al., 2016; Marroni et al., 2010; Molli & Malavieille, 2011): (1) Middle Triassic to Middle Jurassic rifting; (2) Middle Jurassic to Late Jurassic opening of the Ligure-Piemontese oceanic basin, the northern branch of the western Tethys; (3) Late Jurassic to Late Cretaceous filling of the oceanic basin; (4) Late Cretaceous to middle Eocene east-southeastward subduction of the oceanic lithosphere; (5) from early middle Eocene, eastward-southeastward underthrusting of continental crust and onset of continental collision between the Adria and Europe continental margins; and (6) late Eocene-Oligocene subduction reversal with the onset of a westward "Apenninic" subduction and subsequent late Oligocene progressive eastward migration of the foredeep-compressive front system, as a result of the sinking and rolling back of the Adria plate lithosphere (Gueguen et al., 1998; Royden et al., 1987; Scrocca et al., 2007).

We will focus in this section on an overview of the first four steps, from the rifting to the inception of subduction, in order to make a clear picture of the Late Cretaceous geodynamic setting.

2.1. Middle Triassic to Middle Jurassic Rifting

The rifting phase leads to the opening of the Ligure-Piemontese oceanic basin and the configuration of the two Adria and Europe continental margins. The rifting model proposed for the Ligure-Piemontese ocean basin is mainly based on the reconstructed architecture of the deformed and metamorphosed Adria and Europe continental margin pair, currently exposed in the Northern Apennines and Alpine Corsica, and consists of two different rifting steps (Marroni et al., 1998, 2001; Marroni & Pandolfi, 2007). During Middle Triassic rifting affected part of the Variscan suture zone, as a consequence of the Permo-Triassic extensional deformation developed in response of the collapse of the variscan collisional belt (Conti et al., 1993). Rifting at this stage was dominated by lithospheric-scale stretching through pure shear extension, with south and north dipping high-angle faults in the future Europe and Adria continental margin, respectively (e.g., Durand-Delga, 1984, and Froitzheim & Manatschal, 1996, for the Europe margin and Bernoulli et al., 1979, and Bertotti et al., 1993, for the Adria margin). In the Northern Apennines, evidence of this rifting phase can be found at Punta Bianca, in eastern Liguria, where outcrops of a Middle Triassic extensional basin sequence, consisting of marine deposits intercalated with alkaline basaltic flows, are preserved (Stoppa, 1985). In addition, evidence of rifting in the Early Jurassic can be found in the dismembered carbonate platform sequences of the Adria plate margin, as described since the 1980s in the Northern Apennines (Bernoulli et al., 1979), Alpine Corsica (Durand-Delga, 1984), and Western Alps (Bertotti et al., 1993).

A second step of rifting, started at the very beginning of Middle Jurassic, is modeled as dominated by asymmetric, simple-shear kinematics, leading to a different configuration of the paired Adria and Europe continental margins (Marroni et al., 2010, 1998). In this model, the reconstruction of the European Ocean-Continent Transition Zone (hereafter OCTZ) depicts a margin with a sharp ocean-continent transition characterized by exposure of rocks belonging to upper continental crust dissected by high-angle normal faulting. In contrast, and as thoroughly explained in the next paragraphs, the analyses of slide blocks in the Late Cretaceous sedimentary mélanges (e.g., Casanova Complex) (Marroni et al., 2010) of the western External Ligurian Units indicate that the Adria margin was characterized by a wide, magma-poor OCTZ, with exhumed subcontinental lithospheric mantle and lower continental crust covered by extensional allochthons of upper crust such as granitoids or low-grade metamoprhic rocks. This configuration is coherent with an asymmetric extension where a low-angle west dipping detachment fault separated the Adria lower plate from the European upper plate (Marroni & Pandolfi, 2007, and references therein) and shows similarities with what described in the Alps and in the active margin off Iberia by Manatschal (2004).

2.2. End of Middle Jurassic to Late Jurassic Opening of the Ligure-Piemontese Oceanic Basin

Rifting evolves into spreading toward the end of Middle Jurassic (e.g., Bill et al., 2001), with the formation of an oceanic basin whose remnants suggest a formation in a magma-poor, slow-spreading mid-ocean ridge system (Donatio et al., 2013; Lagabrielle & Lemoine, 1997; Sanfilippo & Tribuzio, 2013). As proposed for the Atlantic Ocean (e.g., Godard et al., 2009; Grimes et al., 2008; Schwartz et al., 2005), the alternation of magmatic and amagmatic stages produced an oceanic lithosphere with reduced thickness and a peculiar stratigraphy characterized by serpentinized mantle peridotites, with intruded gabbro bodies, covered by volumetrically limited basalts interfingered with ophiolitic breccias (Abbate et al., 1980; Decandia & Elter, 1972). Well-exposed field examples of this sequence can be found in the Internal Ligurian Units of the Northern Apennines (Marroni & Pandolfi, 2007; Principi et al., 2004) and in the Schistes Lustrés of Corsica (Marroni & Pandolfi, 2007).

2.3. Late Jurassic to Late Cretaceous Filling of the Oceanic Basin

No evidence of oceanic crust younger than Late Jurassic has been found in the Northern Apennines and in the Western Alps and Corsica. Thus, the time span from Late Jurassic to Campanian, that is, the time proposed for the inception of the subduction, is dominated by the sedimentary infilling of the Ligure-Piemontese oceanic basin, which in this phase seems not to be subjected to spreading or convergence. Accordingly, the Callovian to Santonian (about 80 Ma) sedimentary cover of the oceanic lithosphere (Marroni et al., 1992; Principi et al., 2004) lacks any evidence of volcanic activity and/or soft sediments deformations.

2.4. Late Cretaceous to Middle Eocene Subduction of the Oceanic Lithosphere

Early Campanian is universally accepted as the time of the main geodynamic change, with the inception of subduction. The evidence of subduction initiation is provided by the onset of turbidite sedimentation in the entire Ligure-Piemontese oceanic basin (Argnani et al., 2004; Catanzariti et al., 2007; Marroni et al., 1992). This timing is also supported by the occurrence of high-pressure/low-temperature metamorphic ophiolites in both Corsica and the western side of the Northern Apennines, where the ages of the metamorphism range from Late Cretaceous to Early Tertiary (Vitale Brovarone & Herwartz, 2013, and references therein).

Although several authors (e.g., Principi & Treves, 1984) have suggested an evolution of the Northern Apennines through a west dipping subduction zone, most evidence from deformation history and kinematic indicators and the geodynamic constraints all point toward an opposite, east dipping subduction zone for the Late Cretaceous to middle Eocene interval (e.g., Molli & Malavieille, 2011). The west verging, thrusting, and accretion-related deformations (e.g., Van Wamel, 1987; Marroni & Pandolfi, 1996), the high-pressure metamorphism affecting the Europe continental margin before any deformation of the paired Adria margin (Maggi et al., 2012), and the long-lived sedimentation, from Campanian to middle Eocene, of the carbonate turbidites on the thinned Adria continental margin (Marroni et al., 1992), strongly support the existence of an east dipping subduction zone active since Late Cretaceous up to Early Tertiary.

3. Overview of the Ligurian Units of Northern Apennines

The uppermost levels of the Northern Apennines nappe pile are characterized by a complex group of units, generally referred to as Ligurian Units, and classically subdivided in two main groups, namely, the Internal (IL) and External (EL) Ligurian Units (Elter et al., 1966), and representative of two, distinct paleogeographic domains (Figure 2). The IL units comprise a Jurassic ophiolitic sequence, covered by basin plain deposits and a complex turbiditic succession of Late Cretaceous-early Paleocene age (Figure 2b). The EL succession is typically characterized by thick carbonate turbidites of Late Cretaceous age, referred to as Helminthoid Flysch (Figure 2b). The detailed structural and stratigraphic study of Marroni et al. (2001) allowed discriminating between two groups of units in the EL, showing different sedimentary successions at the base of the Helminthoid Flysch (Figure 2b). In the "western EL" units are grouped all successions in which Helminthoid Flysch lies on top of sedimentary mélanges with both oceanic and continental slide blocks, while "eastern EL" units displays a basal Triassic-Jurassic coherent sedimentary succession lacking an ophiolitic component (Marroni et al., 2002, 2001).

Marroni et al. (2001) proposed a Jurassic paleogeographic reconstruction of the western Tethys oceanic basin and its continental margins (Figure 2c), in which the IL represented the Ligure-Piemontese oceanic basin, while the EL units were placed in the wide OCTZ to the Adria margin. In this transitional area, the western EL units are considered to be placed "oceanward," near the Ligure-Piemontese oceanic domain, whereas the eastern EL units represent the distal edge of the Adria continental margin (Figure 2c) (see also Marroni & Pandolfi, 2007, and references therein). In such a paleogeographic configuration, the pronounced differences between the pre-Campanian successions of the western and eastern EL Units have been considered as indicative of two separate sedimentary basins. Therefore, the resulting paleogeographic scenario (Marroni et al., 2001) depicts two sedimentary depressions in the OCTZ, divided since the Late Jurassic by a ribbon of continental crust (Figure 2c), that Marroni et al. (2001) have interpreted as a broader extensional allochthon originated during the latest rifting stages. A similar paleogeographic architecture has been depicted for the margins of the Ligure-Piemontese ocean in the Alpine area (Beltrando et al., 2014; Froitzheim & Manatschal, 1996; Manzotti et al., 2014), where the Sesia-Dent Blanche nappes and the Canavese Zone have been recognized to be representative of the most distal Adriatic margin (see Figure 7 of Manzotti et al., 2014).

The occurrence of ophiolite-bearing clastic debris feeding the sedimentation basin of the EL basal complexes has been considered of crucial importance for the comprehension of the geodynamic evolution of the Northern Apennines, since before the advent of the plate tectonic theory. Elter and Raggi used this observation in the mid-1960s to postulate the existence of the already mentioned "Bracco ridge" that they defined as a "corrugation with an ophiolitic core separating the Ligurian sedimentation area during the Cretaceous" (Elter & Raggi, 1965). In their model the authors provided evidence of deformation through folding and shearing of the rocks of the Bracco ridge, implying that this "corrugation" represented the first stage of convergence in the Ligure-Piemontese oceanic domain, following Aubouin's model (Aubouin, 1965). As introduced, an interpretation of the Bracco ridge in the frame of the plate tectonic theory, as the accretionary wedge built during subduction of the Ligure-Piemontese oceanic plate, was first proposed by Treves (1984)

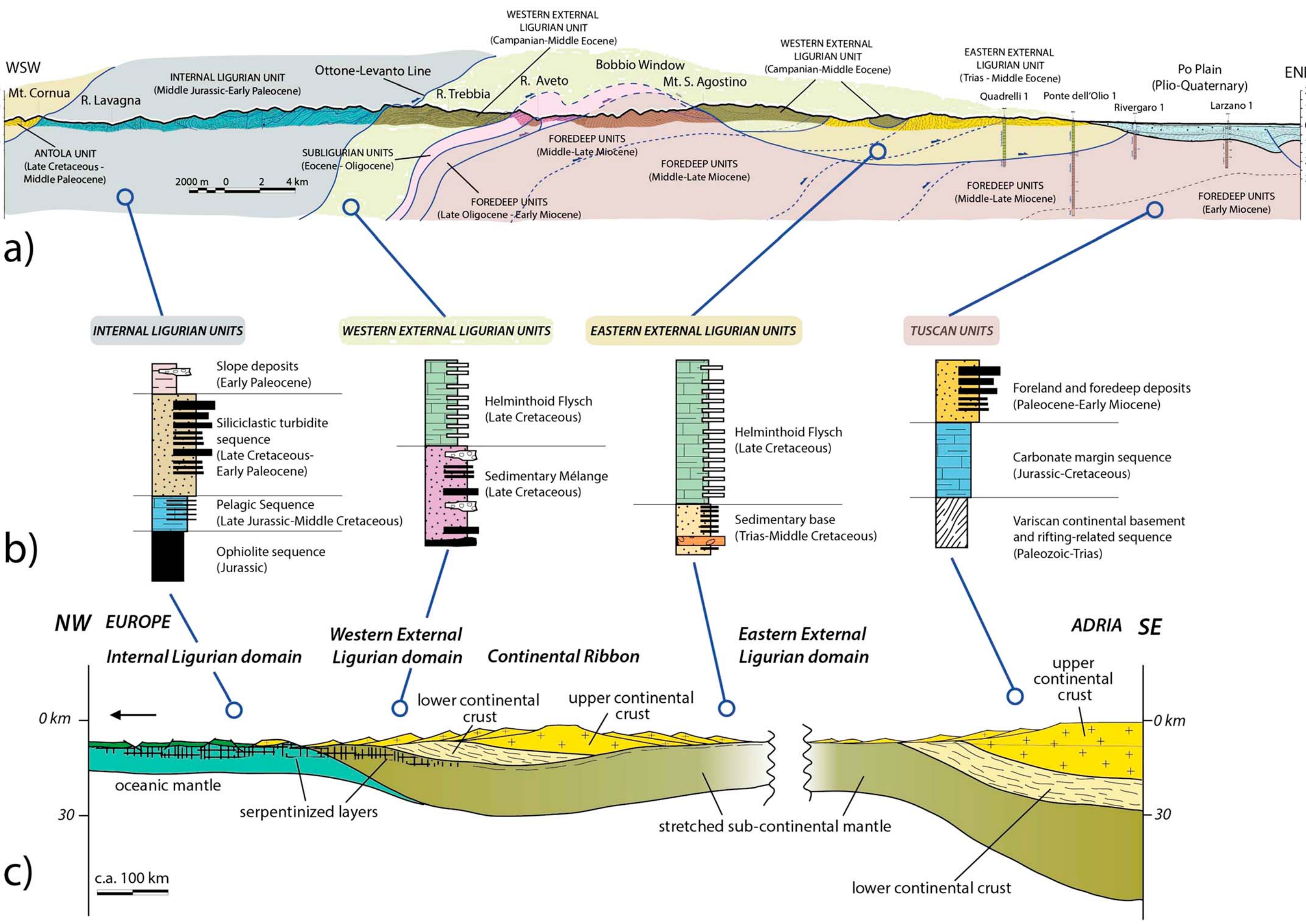

Figure 2. Overview of the tectonostratigraphic groups of units characterizing the Northern Apennines. (a) Regional cross section through the Northern Apennines showing main structural relationships between units. (b) Simplified stratigraphic columns of the reconstructed typical successions characterizing the tectonostratigraphic units. (c) Paleogeographic reconstruction of the Ligure-Piemontese basin and its transition to the Adria continental margin prior to subduction. The inferred paleogeographic position of the units of Figure 2c is indicated.

and then widely accepted in most of the subsequent tectonic reconstructions (Festa et al., 2013; Hoogerduijn Strating, 1994; Malavieille et al., 2016; Marroni, 1991; Marroni et al., 2010; Marroni & Pandolfi, 1996; Meneghini et al., 2007; Molli & Malavieille, 2011; Remitti et al., 2007; Vannucchi et al., 2008 and many others). Some of these contributions focused on various structural aspects of the accretionary wedge (e.g., processes of accretion and mélange formation and circulation of fluids during accretion), some others on the development of the Apenninic wedge in the bigger, regional context of the relationships with the Alpine belt wedge.

4. Evidence for a Campanian-Maastrichtian Double-Vergent Belt

In the following paragraphs we present unpublished data that we collected in the past 20 years of research and we place them side by side with a detailed review of what is already established for the Internal and External Ligurian Units of the Northern Apennines, to show how the Late Cretaceous evolution of this orogeny was dominated by a double-vergent prism. The unpublished data mainly concern the stratigraphic/sedimentological characteristics of the forebelt and retrobelt basins that formed in response to Late Cretaceous subduction. In particular, while there is multiple structural evidence of accretion-related deformation in the front of the prism (see section on the Internal Ligurian Units and the wide literature on these units), the tectonic vergence in the opposite direction can be deciphered essentially from the stratigraphic and sedimentological response to deformation (see data section on the External Ligurian Units).

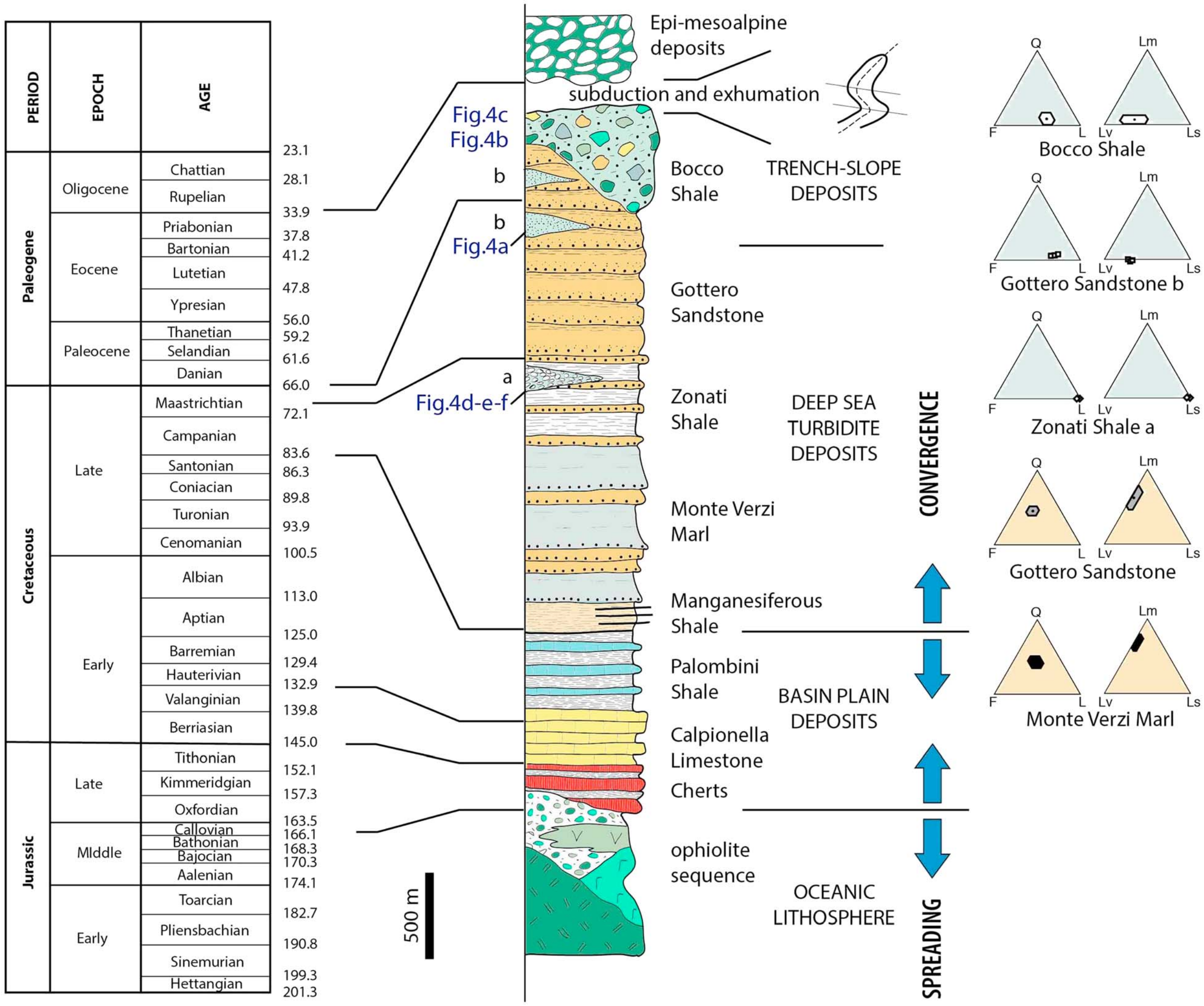

Figure 3. Synthetic stratigraphic log of the Internal Ligurian Units showing the lithologies and the inferred depositional environment of the main formations constituting the sedimentary succession. The framework composition of the different formations and lithofacies is indicated in the right side of the column using Q-F-L and Lm-Lv-Ls triangular diagrams. Diagrams built after data of this study (see also Pandolfi, 1997) and data from Valloni and Zuffa (1984), Van de Kamp and Leake (1995), and Marroni and Pandolfi (2001). The position of the pictures of Figure 4 is indicated.

In this respect, it is worthy to note that Malavieille et al. (2016) proposed for the contact between the Internal and External Ligurian Units, an interpretation as a major back thrust of the Ligurian prism in the retrowedge. Accordingly, we will show here how a well-developed retrowedge matches the stratigraphic characteristics of the depositional basin of the External Ligurian Units.

4.1. Evidence From the Internal Ligurian Units

As well assessed in the literature (Abbate et al., 1980; Cortesogno et al., 1987; Decandia & Elter, 1972; Marroni & Pandolfi, 2007), a complete stratigraphic log of the ocean-derived IL succession can be reconstructed in the Northern Apennines, as comprising a Middle to Late Jurassic ophiolite sequence topped by a thick sedimentary cover, ranging in age from Late Jurassic to early Paleocene (Figure 3).

The ophiolites are characterized by a thin sequence, up to 1 km, consisting of a basement made up of mantle lherzolites, intruded by gabbros and covered by a volcano-sedimentary complex, where sedimentary breccias, basaltic flows, and radiolarites are complexly intermixed (Abbate et al., 1980; Bracciali et al., 2014 and quoted references). This stratigraphy has been interpreted as representative of an ophiolite sequence developed into a slow-spreading ridge (Treves & Harper, 1994 and quoted references). A succession of pelagic/hemipelagic deposits, represented by Cherts (Callovian-Tithonian), Calpionella Limestone

(Berriasian-Valanginian), and Palombini Shale (Valanginian-Santonian), cover the ophiolite sequence in all IL Units. The Cherts derived essentially from the reworking of pelagic siliceous ooze by turbidites and oceanic bottom currents, whereas the Calpionella Limestone and the Palombini Shale derived from distal carbonatic and mixed siliciclastic-carbonatic turbidites, mainly from a source area located in the uppermost part of the Europe/Corsica continental margin (Bracciali et al., 2007; Pandolfi, 1997). The Palombini Shale grades upward to a complex turbiditic succession, mainly of siliciclastic composition, ranging from Campanian to early Paleocene (Figure 3). On the basis of the sedimentology of the turbidites, this system has been subdivided into several formations, all interpreted as belonging to a fan system fed by the Europe-Corsica continental margin (Nielsen & Abbate, 1983): this turbiditic complex offers several stratigraphic and sedimentological evidence of a thickening prism at Late Cretaceous time (Figure 3). The Bocco Shale, of early Paleocene age, is the youngest formation of the IL typical sequence that unconformably lies on top of all the older formations.

The lower part of the complex features siliciclastic basin plain turbidites (Manganesiferi Shale, early Campanian) that, upward in the succession, are interrupted by interbedded events of carbonatic megaturbidites (Monte Verzi Marl, early to late Campanian). The upper part of the turbidite system is composed of a thickening and coarsening upward turbiditic sequence, with predominant siliciclastic composition, comprising the Zonati Shale (cfr. Ronco Formation and Canale Formation, late Campanian-early Maastrichtian) and the Monte Gottero Sandstone (early Maastrichtian-early Palaeocene). While the Zonati Shale (cfr. Ronco Canale Formations), is made by thin-bedded turbidites, interpreted as basin plain deposits, the Monte Gottero Sandstone features coarse-grained siliciclastic turbidites that have been interpreted as the proximal portion of the deepwater fan. The data collected in several PhD and undergraduate projects of stratigraphic and petrographic analyses of this turbiditic complex suggest that the arenites from Val Lavagna Shale Group, Monte Gottero Sandstone, and Bocco Shale are arkoses and subarkoses characterized by an almost complete siliciclastic framework (Figures 3 and 4) (see, e.g., Pandolfi, 1997), dominated by monocristalline quartz and feldspar fragments, and by a lithic fragments component represented by granitoids and very low-grade metamorphic rocks such as micaschists and gneisses. According to the interpretation of Abbate and Sagri (1982), Nielsen and Abbate (1983), and to similar data from Valloni and Zuffa (1984) and Van de Kamp and Leake (1995), we can interpret the facies identified in the various turbiditic formations as representative of a fan system that developed at the foot of a passive continental margin and its transition to an ocean basin. In particular, the continental crust-derived material detected in the arenitic intervals allows identifying the upper part of the Corsica-Europe continental margin as the main source area, and the area of connection between this margin and the deep-sea Ligure-Piemontese basin, as the location of formation of the fan system (Figure 3) (Marroni & Pandolfi, 2001; Pandolfi, 1997; Valloni & Zuffa, 1984; Van de Kamp & Leake, 1995).

In addition, we found that the upper part of the Monte Gottero Sandstone coarse-grained arenites (F8 + F9 facies of Mutti, 1992) typically contains lithic fragments of serpentinites, basalts, radiolarites, Calpionella-bearing limestones, and siliciclastic sandstones and siltstones (Figures 3 and 4a). The succession, therefore, seems to record the progressive involvement of the fan system and the basin hosting it, into subduction and trench systems. We can correlate the source of these lithoarenites to the IL Jurassic ophiolite sequence and the related Late Jurassic-early Paleocene sedimentary cover.

A further confirmation to the hypothesis of a double-vergent prism structured since Late Cretaceous, comes from the Bocco Shale, the youngest formation of the IL succession that Marroni and Pandolfi (2001) interpreted as a tectonically controlled deposit of early Paleocene age, and unconformably lying on the older formations (Figure 3), from the Palombini Shale to Monte Gottero Sandstone (Marroni & Pandolfi, 1996). The Bocco Shale consists of thin-bedded turbidites, interbedded with ophiolite-bearing slide and debris flow and high-density turbidity current-derived deposits. While the thin-bedded turbidites show a facies association derived from evolved low-density turbidity currents, the facies analysis and provenance studies on the slide and debris flows deposits indicate a formation by small and scarcely evolved flows that reworked a typical oceanic lithosphere and its sedimentary cover. Marroni and Pandolfi (2001) interpreted these processes as the consequence of submarine landslides developed along a steep slope and concluded that the gravity-related deposits of the Bocco Shale were supplied by the ophiolites and the sedimentary deposits already incorporated at the base of the accretionary wedge (Figures 4b and 4c). The stratigraphic transition from deposits alimented by the upper continental

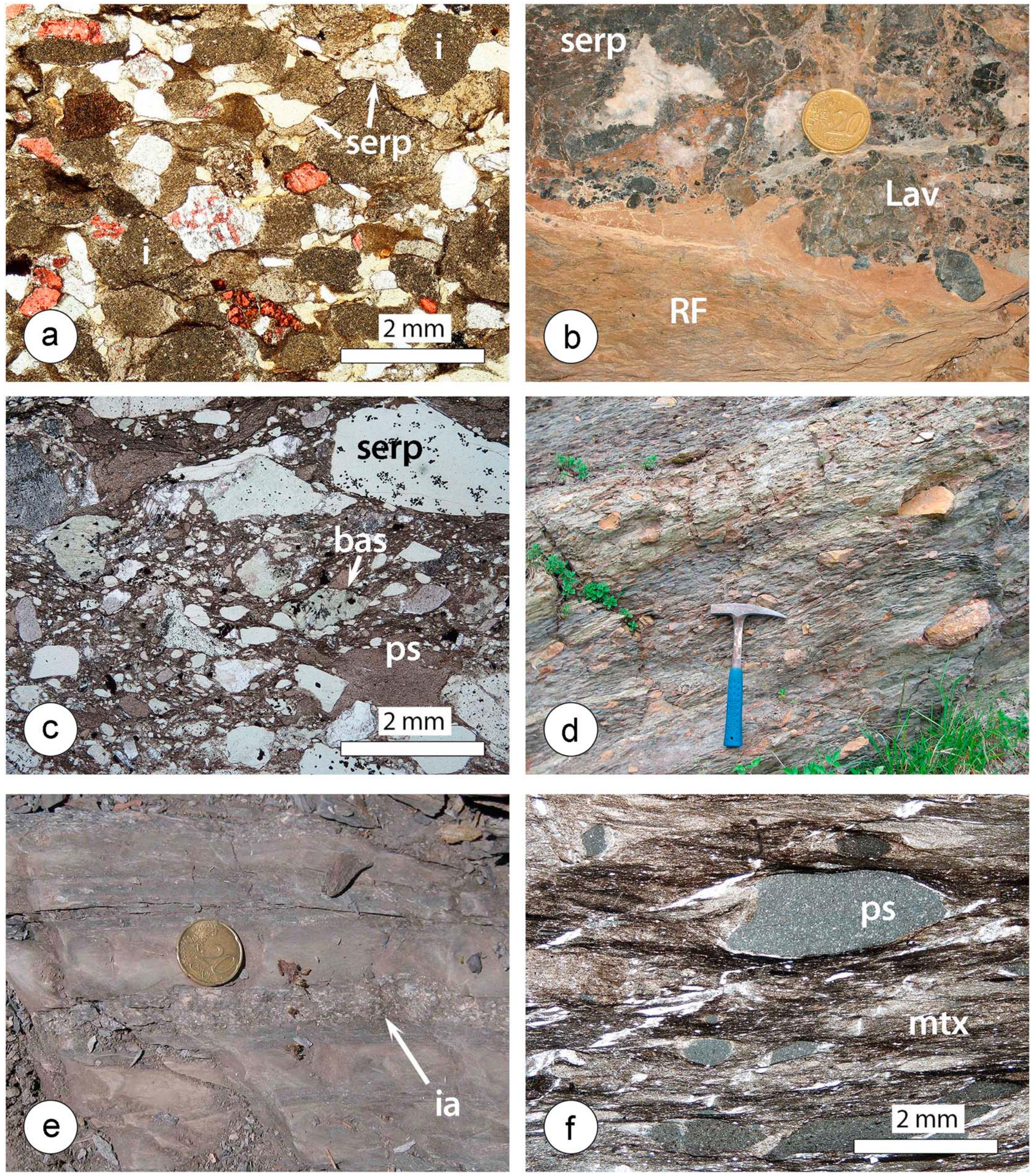

Figure 4. Field- and microscopic-scale characteristics of the Internal Ligurian Units formations (location of pictures in Figure 3). (a) Ophiolite-bearing lithoarenites from Gottero Sandstone (serp, serpentinite fragment; i, siliciclastic fine-grained intraclast); (b) stratigraphic relationships between Ronco Formation (RF, cf. Zonati Shale) and the ophiolite-bearing breccia belonging to Lavagnola Formation (Lav,. cf. Bocco Shale), serpentinite fragment are indicated (serp); (c) photomicrograph of the ophiolite-bearing lithoarenites associated with the Bocco Shale (serp, serpentinite fragment; bas, basalt fragment; ps, Palombini Shale fragment); (d) cohesive debris flow in the Lavagnola Fm (cf. "olistostroma di Passo della Forcella" in the Zonati Shale); (e) high-density turbidity current derived deposits (ia, intrarenite in the Zonati Shale) associated to the "olistostrome" deposits; and (f) photomicrograph of the olistostrome matrix (mtx). A clast of Palombini Shale calcilutite (ps) is indicated.

margin of Europe-Corsica to ophiolite-bearing deposits is well visible at the Ronco Formation (cf. Zonati Shale) and Lavagnola Formation (cf. Bocco Shale) boundary (Figures 4b and 4c). Therefore, the Bocco Shale deposits most probably sedimented into the trench, tapering the above described deep-sea fan system of the Ligure-Piemontese basin and were successively subjected to deformation and metamorphism while being themselves incorporated into the accretionary prism. The authors propose a mechanism of frontal tectonic erosion (e.g., Clift & Vannucchi, 2004), as the one likely active to form these tectonic- and gravity-controlled deposits.

One of the most important finding from provenance analyses on the Bocco Shale comes from a study on the Pian di Cavallo Breccia, a lithofacies belonging to the lower section of the formation (Marroni, 1987). This study highlighted the occurrence of clasts of various lithologies, indicative of different sources feeding the area of deposition of the Bocco Shale, and featuring not only ophiolite-derived clasts (serpentinites, gabbros, basalts, cherts, Calpionella bearing limestone, and feldsphatic arenites) but also clasts representative of upper continental crust, such as cataclastic granitoids, micaschists and garnet-bearing paragneisses, and clasts derived from the lower continental crust, such as orthopyroxene-bearing felsic granulite.

The Campanian-Maastrichtian time interval is punctuated by several other events of tectonically controlled sedimentary deposition throughout the IL succession, as indicated by the Zonati Shale and the Monte Gottero Sandstone turbiditic successions, both showing various intercalations of debris flow (Figure 4d) and deposits from high-density turbidity current (Figure 4e), analogous to that of Bocco Shale (Marroni & Pandolfi, 2001); and different feeding source areas that have been documented in various beds of the turdibiditic systems of the Zonati Shale, Ronco Formation, and Canale Formation (Figure 3). Fierro and Terranova (1963), for example, described for the first time a mappable level of debris flow deposits in the Zonati Shale that they named "olistostroma del Passo della Forcella." These deposits consist of centimeter- to decimeter-sized clasts in a shale-dominated matrix (Figure 4f) showing stratigraphic relationships with the Zonati Shale and interpreted by Elter and Raggi (1965) as supplied by the Bracco ridge tectonically controlled structure. The petrographic analyses we have performed on samples from the olistostroma del Passo della Forcella reveal that the debris flow contains clasts belonging to the Palombini Shale and Calpionella Limestone (Pandolfi, 1997).

As a whole, the described sedimentological features of the IL turbiditic complex, such as (i) their stratigraphical lower boundary with pelagic, basin plain deposits and (ii) the transition from a source located in the upper part of a continental margin to a more proximal alimentation from an active prism (Figure 4b), able to provide ophiolitic-bearing debris (Figure 4c), all reflect the trenchward motion of an area belonging to the Ligure-Piemontese oceanic basin (Marroni et al., 2010; Treves, 1984). Therefore, the presented data strongly confirm the hypothesis of a Ligure-Piemontese oceanic basin sedimentary activity controlled by a tectonic structure active since late Campanian and up to early Paleocene, with the sedimentation basin fed by a passive continental margin first, and then by a tectonically controlled morphological structure.

There is no dating on the age of the deformation phases recorded by the IL successions, but di Biase et al. (1997) provided a relative age estimate of these folding phases from indirect observations in the Val Borbera Conglomerates of the Tertiary Piedmont Basin (Figure 3). The Tertiary Piedmont Basin is an episutural basin that developed onto the Alpine and Apennines orogens and sealed the Late Cretaceous to Eocene evolution. In the cited paper, the authors reported a petrographical and microstructural study on deformed low-grade metamorphic pebbles belonging to the Val Borbera Conglomerate. They described two phases of folding in these blocks and found that the features of these pebbles allow reconciling them to the lithologies of the IL. Then, they suggested that these deformations affected the rocks of the IL before their subaerial erosion to supply the basin of deposition of the conglomerates. Therefore, they concluded that these folding phases are older than the early Oligocene Val Borbera Conglomerates and ascribable to the Eocene-early Oligocene boundary.

4.2. Evidence From the External Ligurian Units

The EL successions also offer several points of evidence supporting the hypothesis that, during Late Cretaceous, the Northern Apennines were largely structured in a precollisional, tectonically controlled structure, tens of million years before continental collision between Adria and Europe.

As introduced, the EL are typically characterized by the widespread occurrence of the Late Cretaceous carbonate Helminthoid Flysch (Figure 2) but can be classified in two different groups according to different basal successions (Marroni et al., 2010, 2002, 2001; Marroni & Pandolfi, 2007): (i) the western EL successions (i.e., outcropping in the westernmost sector of the EL area of exposure) are featured by very thick sedimentary mélanges at the base of the Helminthoid Flysch, whereas (ii) the eastern EL successions (i.e., outcropping in the easternmost sector of the EL area of exposure) typically display a Triassic-Jurassic sedimentary base in the same stratigraphic position (Figure 2).

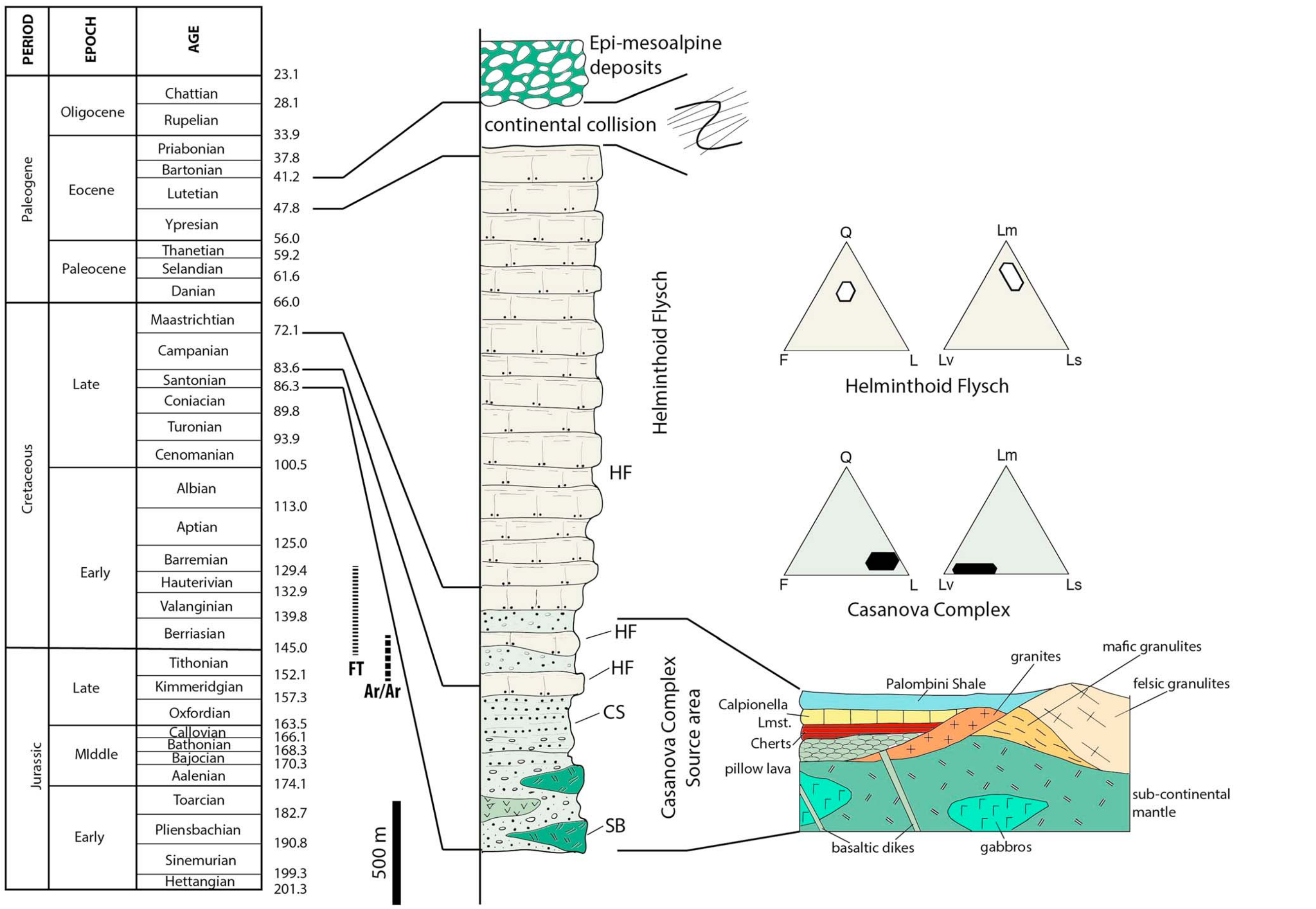

Figure 5. Synthetic stratigraphic log of the western External Ligurian Units showing the lithologies of the main formations constituting the sedimentary succession. In particular, the inferred configuration of the source area of the ophiolite-bearing basal complex (cf. Casanova Complex), is also indicated, as forming the original sequence stratigraphically underlying the Helminthoid Flysch. SB, slide block of mantle ultramafic; CS, Casanova Sandstone; and HF, Helminthoid Flysch. The framework composition of the different formations and lithofacies is indicated in the right side of the column, using Q-F-L and Lm-Lv-Ls triangular diagrams. Diagrams built after data of this study (see also Pandolfi, 1997), and data from Di Giulio and Geddo (1990).

A detailed analysis of the western EL sedimentary mélanges offers unequivocal evidence of a Late Cretaceous precollisional wedge structure. The typical EL mélange is a coarse-grained, chaotic deposit composed of polymictic slide blocks with size ranging from the centimeter scale to blocks on the order of 30 km^2, dispersed in a fine-grained argillitc and varicoloured matrix (Figures 5 and 6). Slide blocks comprise the following rock types:

1. depleted ultramafics, essentially spinel lherzolites. They commonly show a well-developed tectonite-mylonite fabric defined by pyroxenite bands (Piccardo et al., 2004). The study of Piccardo et al. (2004) suggested an interpretation of these rocks as slices of subcontinental mantle that was emplaced at depth at Jurassic time during the early stages of rifting and opening of the Ligure-Piemontese basin;
2. mafics lithotypes, such as troctolite to olivine-bearing gabbro, pillow lava, and massive basalts. Gabbro blocks are locally deformed by localized, ductile shear zone, while basalts frequently show stratigraphical transitions to radiolarian cherts that have been dated to Late Callovian-Early Oxfordian (Conti et al., 1985). The petrogenesis of these mafic rocks suggests an origin from MOR-derived melts (Montanini et al., 2008). In particular, basalts show a normal to transitional MOR geochemical affinity;
3. basalt dykes are ubiquitous both in mafics and ultrmafics rocktypes;
4. sedimentary blocks ascribable to the Palombini Shale, Calpionella Limestone and Cherts formation (Figure 6), that is, representative of the sedimentary cover of the Ligure-Piemontese oceanic basin(Elter et al., 1991; Marroni et al., 1998);

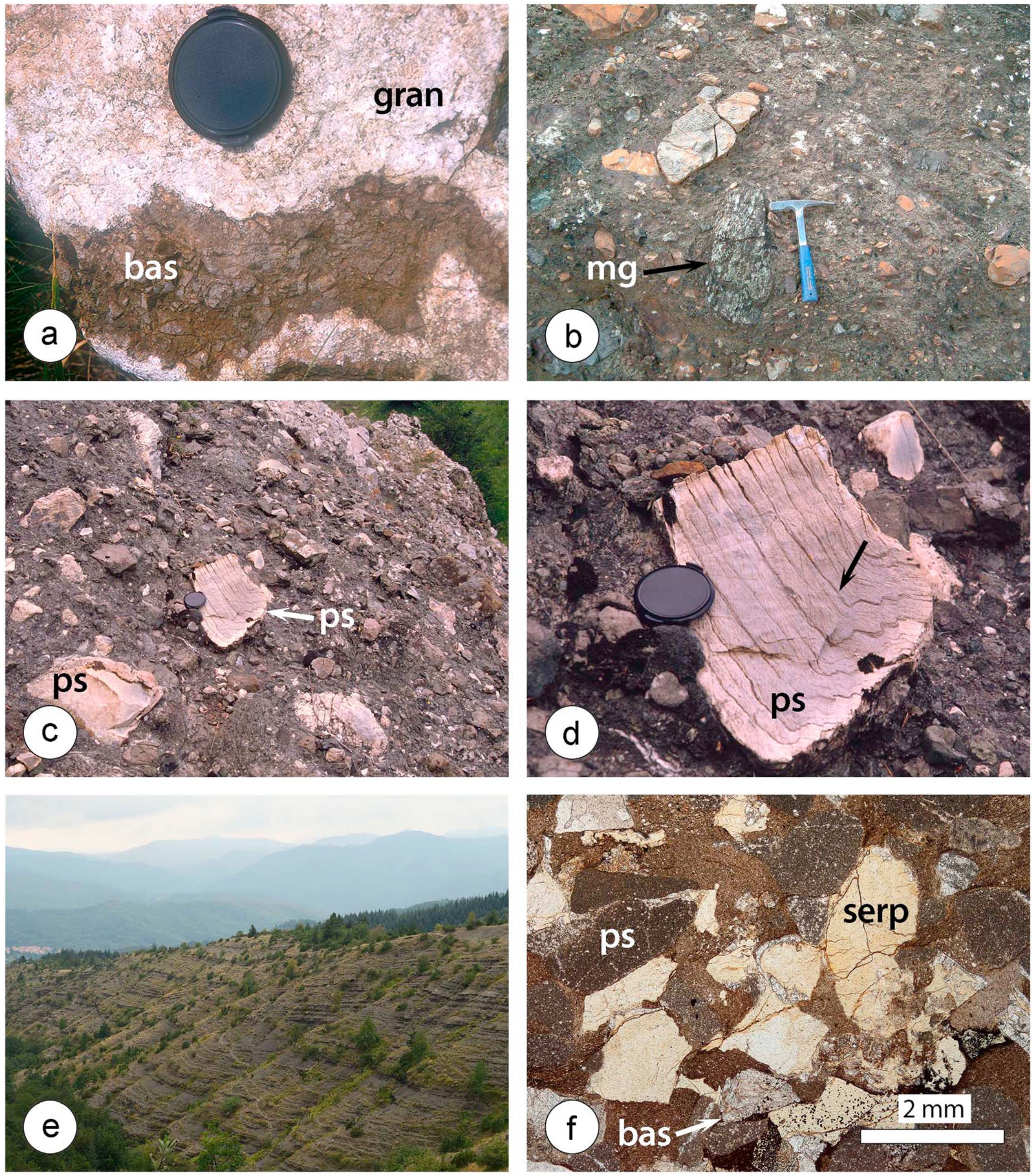

Figure 6. Field- and microscopic-scale characteristics of the western External Ligurian Units formations. (a) Primary relationships between cataclastic granites (gran) and basalts (bas) preserved inside a slide block of the Casanova Complex; (b) mafic granulites (mg) clast preserved in a matrix supported breccia of the Casanova Complex; (c) hyperconcentrated flow-derived breccia in the Casanova Complex. Clasts of Palombini Shale calcilutites are indicated (ps). A folded foliation inside the ps clast is indicated with the white arrow; (d) close-up of the Figure 6c showing folded foliation in ps clast. Note that the foliation is limited to the clast and does not affect the breccia matrix; (e) field aspect of the Casanova Sandstone close to the Casanova village; and (f) photomicrograph of the ophiolite-bearing Casanova Sandstone lithoarenites. Fragments of basalt (bas), serpentinite (serp) and calcilutites belonging to the Palombini Shale (ps) are indicated.

5. granitoids, typically deformed by cataclastic shear zones that Marroni et al. (1998) estimated as formed prior to Middle Trias. Molli (1996) reported for these blocks intrusions by basaltic dikes or basalt flows stratigraphically capping both the granitoids and the cataclastic deformation zones. Ferrara and Tonarini (1985) radiometric dating established a Paleozoic age for the formation of these granitoids (310–280 Ma);
6. mafic granulites (Figure 6b). The compositional, structural, and petrologic characteristics of these slide blocks were extensively studied by Marroni and Tribuzio (1996) and Montanini (1997) that both considered them as formed from crystallization of tholeiite-derived melts that were contaminated by crustally

derived liquids. The preserved igneous textures and the geochemical characteristics suggest that these rocks intruded at deep structural levels into an extending continental lithosphere, and then reequilibrated under granulite facies (0.6–0.9 GPa and 810–920°C) in the Late Carboniferous-Early Permian time (Meli et al., 1996). Exhumation to upper crustal levels is recorded by a retrograde metamorphic evolution from granulite to amphibolite and greenschist facies conditions, associated with a transition from plastic to brittle deformation (Marroni et al., 1998), and estimated as younger than Middle Triassic (Meli et al., 1996);

7. garnet-bearing acid granulites. Marroni et al. (1998) interpreted them as the metamorphic equivalent of sedimentary rocks and described a post-Late Paleozoic retrograde metamorphic history from granulite to amphibolite and greenschists facies conditions that accompanied mylonitic as well as cataclastic deformation; and
8. micaschists, ortogneisses, and garnet-bearing paragneisses are also occasionally found in polymictic breccias.

The age of the mélange suggests a formation through a catastrophic event restricted to the late Santonian-early Campanian time interval.

As described, most of the continental- and ocean-derived slide blocks record a tectonometamorphic history that can be correlated to the extensional phases that resulted in the Ligure-Piemontese basin opening. In addition, evidence of subsequent deformations are commonly found in the limestones and cherts clasts from the oceanic sedimentary cover, in the form of folding and foliation development (Figures 6c and 6d) and brecciated textures.

The slide blocks hold a deformation and metamorphism history that is not shared with the sedimentary matrix, where the above described deformation is totally lacking (Figure 6d): the blocks were therefore subjected to tectonometamorphic events before their inclusion into the sedimentary mélange. This hypothesis is supported by radiometric dating of the garnet-bearing granulites and the mafic granulites, which indicated an age of deformation at the Santonian-Campanian boundary. For instance, Balestrieri et al. (1997) have identified in the slide blocks of quartz-feldspathic granulites a partial annealing of the fission tracks of zircons at 80 Ma (Figure 5). This reset is due to a thermal overprint over the closure temperature of 240 + 50°C (Hurford, 1986). In addition, Meli et al. (1996) have described a greenschist metamorphism (phrenite-pumpellyte facies) in the mafic granulite that has been related to a $^{39}Ar/^{40}Ar$ age of 81.5 + 2.5 Ma detected in the plagioclases (Figure 5). Generally, the blocking T for the Ar retention in plagioclase is regarded as lower than 200–250°C (e.g., Maluski et al., 1990). In summary, a metamorphic event at pressure-temperature conditions typical of the prehnite-pumpellyte facies affected the mafic rocks found as slide blocks in the mélange at the Santonian-Campanian boundary.

This metamorphic event predates the very low grade metamorphism of Tertiary age described in the western EL by Molli et al. (1992). These authors, on the base of illite and chlorite crystallinity and phyllosilicate paragenesis, have suggested that the sedimentary matrix of the mélange has reached only the diagenetic condition, with a maximum temperature lower than 200°C. Very recently, Malavieille et al. (2016) have conducted a thermometry study to characterize the metamorphic peak of the Casanova EL mélange and overlying IL units. The results highlight that the slide blocks of the mélange experienced a different and deeper thermal history with respect to the mélange matrix, with peak temperature of approximately 250°C and $<$210°C, respectively.

As a whole, all the evidence strongly indicates that the sedimentary mélange formed by incorporation of different rocks recording an older tectonometamorphic history.

The facies association preserved in the western EL mélange provides also important hints on the nature and evolution of its area of deposition. The mélange holds facies indicating deposition from slides, cohesive debris flows, hyperconcentrated flows and high-density turbidity currents (Figure 6c), and fine-grained thick-bedded turbidites (Figure 6e), typically referred to as Casanova Sandstone (see Passerini, 1965 for the first definition; Elter et al., 1991). We performed petrographic analyses on the Casanova Sandstone and all analyzed samples point to a lithoarenitic composition dominated by ophiolite-derived fragments (Figures 5 and 6f); similar compositions were obtained by the study of Di Giulio and Geddo (1990) (Figure 5). Moreover, some stratigraphic features we detected in the Casanova Sandstone, such as the presence of ponding and rebounding structures and an extremely high pelite/arenite ratio, suggest that these fine-grained turbidites were trapped in a strongly confined basin. The mélange typically includes huge, plurihectometer-scale slide blocks that are everywhere intimately associated with matrix- to clast-supported breccias and turbidite-derived rudites, arenites, and pelites, forming a peculiar facies association where proximal and distal facies are mixed together. According to the large thickness of the sedimentary mélange (approximately 2,000 m) (Marroni et al., 2001) and the short time of sediment accumulation, estimated around 5–6 Ma, we can hypothesize that the western EL mélange formed in a distinct and confined basin as a consequence of a catastrophic and chaotic sedimentation event restricted to the late Santonian-early Campanian time span and related to tectonic events that affected both the source area and the basin itself.

A similar evidence of late Campanian tectonics is recorded also in the lowermost stratigraphic levels of the Helminthoid Flysch, where the carbonate turbidites are interbedded with deposits originated by slides and cohesive debris flows, as well as by hyperconcentrated flows and high-density turbidity currents. It is worth noting that, after this tectonic event, the western EL basin lasted unaffected by synsedimentary deformations up to middle Eocene, that is, until the onset of continental collision. In fact, from Maastrichtian up to middle Eocene the western EL basin is characterized by the continuous, monotonous sedimentation of the carbonate turbidites of the Helmithoid Flysch, followed by the turbidites of the Tertiary Flysch Auctt (Catanzariti et al., 2007; Marroni et al., 2010, 1992). The typical Helminthoid Flysch calcareous turbidites consist of rhythmic alternation of calcareous-marl, marly-limestone, and marl layers showing medium to very thick beds with fine to medium arenitic base. These layers typically show an a/p ratio $\ll 1$ that, in some layers, can reach values >20. The arenites show an arkosic composition (Figure 5) characterized by monomineralic fragments of quartz, feldspar, and rock fragments derived from granitoides and low-grade metamorphites. These features, the presence of incomplete Bouma sequences, the lack of erosive structures, the parallel plane geometry of the strata, and the carbonate-free hemipelagic background sediments, indicate a deposition by low-density turbidity currents in a deep-sea environment (abyssal plain) located below the local $CaCO_3$ compensation level (Marroni et al., 1992; Scholle, 1971).

5. Tectonic Origin of a Precollisional Double-Vergent Belt: A Discussion

In the following sections we try to put together the structural and stratigraphic data provided in this contribution with what is already known from literature, to draw the configuration of the Ligure-Piemontese branch of the western Tethys at the beginning of subduction, and we show how this scenario can be used to: (i) propose a model of subduction initiation for the Northern Apennines located at the transition between the oceanic plate and the thinned Adria margin (Figures 7 and 8); (ii) confirm a structuration of a double-vergent belt well before continental collision (Figures 7–9); and, as a corollary, (iii) suggest how this scenario might have controlled a reversal in subduction in the Apennine system (Figure 9). A paragraph is also dedicated to highlighting how, the proposed nature of the Ligure-Piemontese basin margin at the Adria side, matches the main requirements for subduction initiation at the ocean-continent boundary zone, as postulated through buoyancy analyses, analogue, and mathematical modeling of subduction initiation.

5.1. The Bracco Ridge Revisited: A Double-Vergent Precollisional Embryo of the Northern Apennines Orogen

The provided stratigraphic, sedimentological, and structural characteristics of the IL and EL units strongly indicates that the Santonian-Campanian time interval was dominated by voluminous debris production that fed both areas of deposition of the IL and western EL successions. This suggest that both basins were located in the proximity of a tectonically active, morphologically elevated structure, that can be possibly identified in the preplate tectonic Bracco ridge structural high of Elter and Raggi (1965), and for which an interpretation in terms of an active accretionary wedge has been proposed since the 1980s (Treves, 1984). According to this interpretation, the Late Cretaceous evolution of the IL and western EL basins was controlled by an active accretionary prism, connected to an east dipping subduction zone (Hoogerduijn Strating, 1994; Marroni, 1991; Marroni & Pandolfi, 1996; Marroni et al., 2010, 2004; Molli & Malavieille, 2011), that represented the main feeding source of sediments for both basins (Figure 7).

Most recent geodynamic reconstructions of the Late Cretaceous Apenninic subduction system depict a double-vergent structure with a well-developed retrobelt thrust sheet system contemporaneous to the main one in the forebelt (Malavieille et al., 2016; Marroni et al., 2010): a precollisional, well-developed double-vergent orogen has been postulated also for the Cretaceous evolution of the Alps (Zanchetta et al., 2012), in accordance with geological, mechanical and numerical models (Doglioni et al., 2007; Willett et al., 1993).

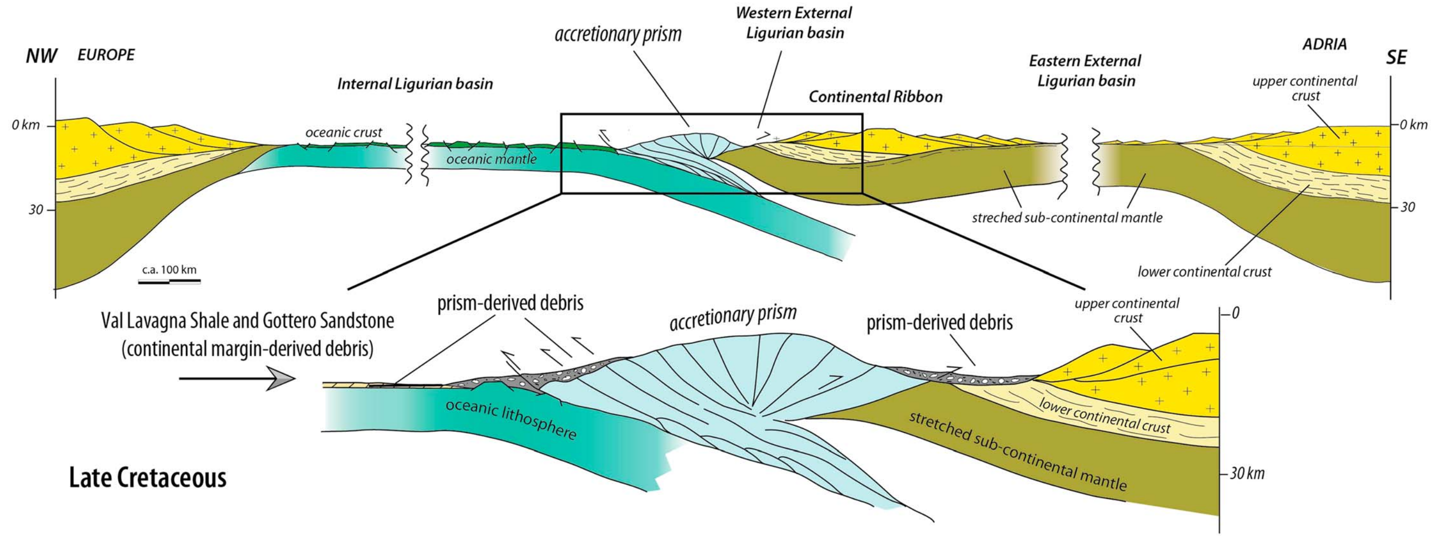

Figure 7. Schematic section across the Ligure-Piemontese basin at Late Cretaceous time. Subduction is active and an accretionary prism is growing between the basins of deposition of the succession of the Internal Ligurian Units (IL) and western External Ligurian Units (WEL). The WEL basin is isolated from that of deposition of the eastern External Ligurian Units succession by a regional-scale continental block that can be correlated to the Sesia-Dent Blanche units of the Alps. In the close-up view at the bottom, the prism-derived debris is shown as feeding both IL and WEL basins with already deformed and metamorphosed rocks from the prism. Approximate location of section is shown in Figure 8.

According to this scenario, the back thrusts in the accretionary prism propagated above and within the retrobelt basement to incorporate the sedimentary and basement materials into the rear of the accretionary prism (Figure 7). The materials incorporated into the retrobelt thrust sheet system subsequently represented the source area for the sedimentary mélange. Therefore, while the deformation front produced debris that was channeled into the IL depositional system of the trench, the western EL mélange formed in a retrobelt setting fed by material produced by deformation and retrowedge tectonics. A retrowedge setting for the formation of the western EL successions was already hypothesized by Marroni et al. (2010) and recently strengthened and reproduced by modeling in Malavieille et al. (2016). In particular, the experimental models of Malavieille et al. (2016) indicate how a path of ophiolite accretion and burial in the wedge, followed by exhumation through backtrusting and gravity-driven processes in the retrowedge, could produce the ophiolitic debris in the western EL Casanova Complex mélange.

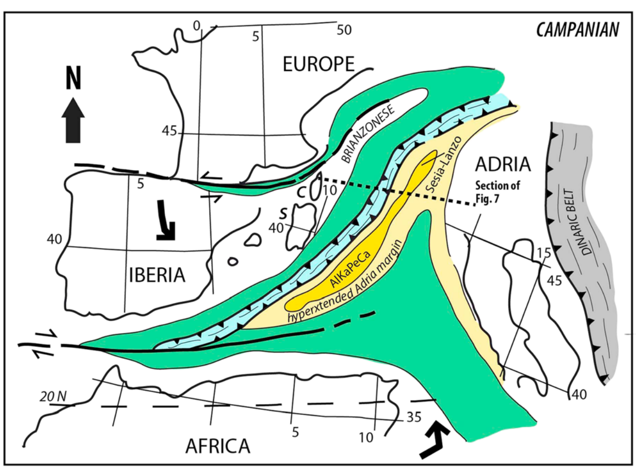

Figure 8. Map view of the Mediterranean area and the Alpine-Apennines subduction system, at 80 Ma (Campanian time), with location of the cross section in Figure 7. Positions (coordinates) and displacements (black arrows) of Africa, Iberia Adria versus Europe, and position of Corsica-Sardinia (C and S, respectively) versus Iberia, based on the study of Michard et al. (2002). Similarly to the other figures, yellow areas are continental domains (light yellow represents thinned continental margins), green represents the Ligure-Piemontese oceanic basin, and light blue is the growing accretionary prism. The Dinaric belt on the east is also shown in gray color.

5.2. Inferred Location of the Northern Apennines Doubly-Vergent Accretionary Wedge

The voluminous coarse-grained debris found in both the IL and western EL successions comprise not only ophiolite and suprao-phiolitic sediments-derived rocks, and/or crustal material from a continental margin, but, most importantly, contains clasts derived from the subcontinental mantle. The clasts found in the western EL mélange have interpreted as related to the OCTZ side of the Adria continental margin, since the beginning of this century (Marroni et al., 2001), as this setting provides the occurrence of a large-scale low-angle detachment fault that can account for the exhumation and exposure of subcontinental mantle (Schaltegger et al., 2002). Lower continental crust granitoids and granulites have been detected in the lower section of the Bocco Shale by Marroni (1987), which, however, failed to propose an origin for these blocks or place them in a reasonable tectonic model. We propose here

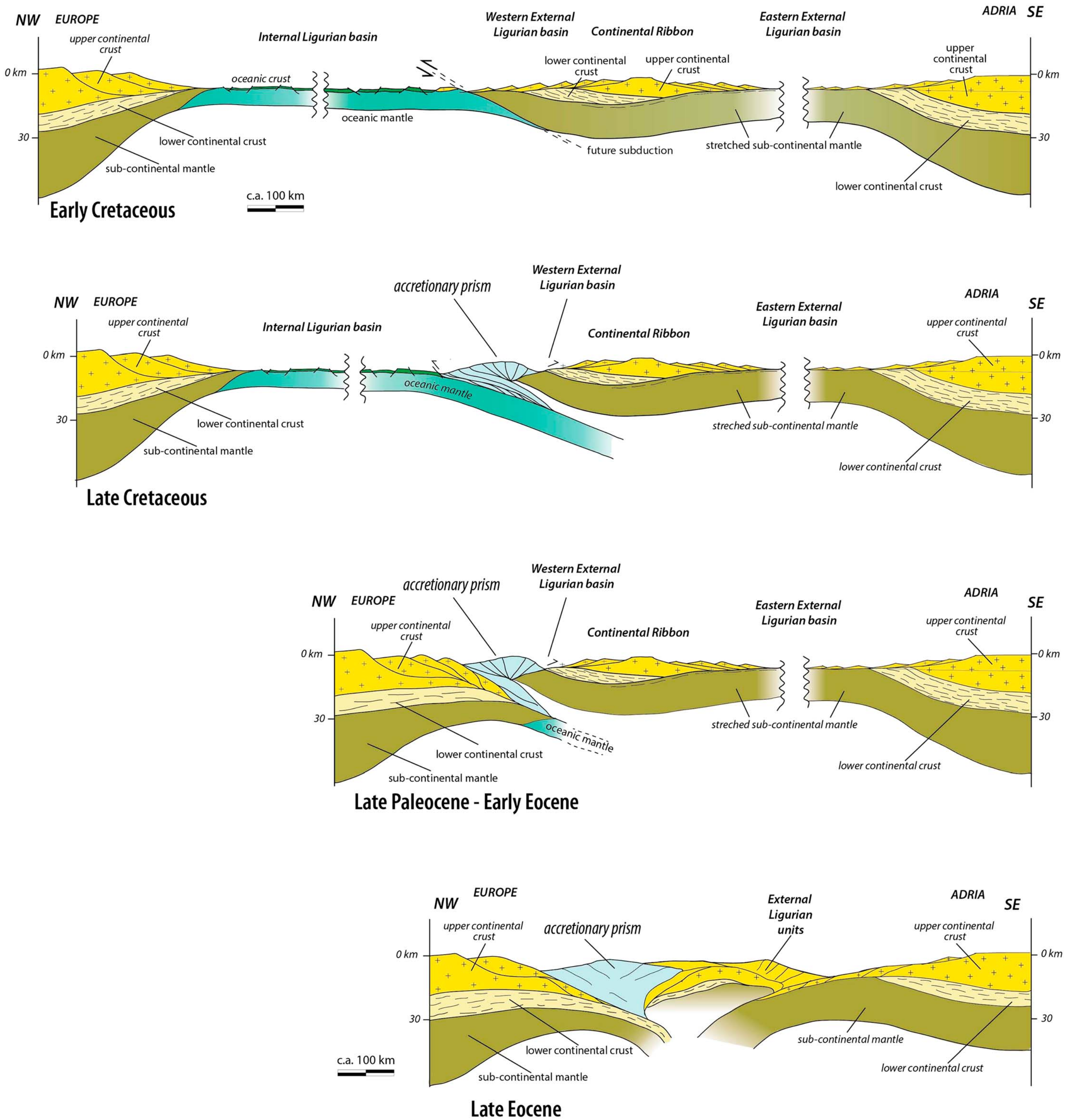

Figure 9. Evolutionary model of the Northern Apennines comprising: The end of the spreading phase (Early Cretaceous), the Late Cretaceous Alpine subduction, the late Paleocene-early Eocene onset of continental collision, and the late Eocene flip of subduction and onset of westward "Apennines" subduction and collision.

that these blocks derived from the same thinned transition zone to the continental margin. In Alpine Corsica (i.e., the southern extension of the Ligurian Northern Apennines), the juxtaposition of continental basement, ultramafic rocks, and Mesozoic sediments, all showing a variable subduction-related, high-pressure/low-temperature metamorphic imprint has been observed by several authors (Meresse et al., 2012; Vitale Brovarone et al., 2011) that have interpreted the continental rocks as former extensional allochthons of continental crust abandoned during rifting and then buried at depth during subduction. More recently, Manzotti et al. (2014) have proposed a similar involvement of slices of thinned Adria margin into Late Cretaceous subduction to explain the Alpine evolution of the Sesia-Dent Blanche nappes of the Alps. In-line with this regional picture of the Alpine-Apennine system, we propose that not only the Santonian-Campanian time interval was dominated by an active, thickening accretionary wedge, but that this structure grew by accretion and incorporation of slices of Ligure-Piemontese oceanic material, as well as of fragments of the transitional area between the oceanic realm and the Adria continental margin and (Figure 7), now preserved in the high-grade units of Alpine Corsica and in the lower grade Internal Ligurian Units. Therefore, the wedge must have been located in the close proximity of the ocean-continent transition to the Adrian thinned margin so that also extensional allochthons of upper crust and portions of the exposed subcontinental mantle could be buried during subduction, contribute to prism thickening, and be redeposited as debris both in the forewedge and retrowedge basins. The continental-derived blocks, as well as those derived from the oceanic magmatic basement and the oceanic sedimentary cover, found in the western EL mélange of the retrowedge, contain a tectonometamporphic history older that the one recorded in the mélange matrix, and that has been dated at circa 80 Ma: we propose that this deformation and metamorphic event reflects the incorporation into the Late Cretaceous accretionary wedge, located over an east dipping subduction zone that initiated at the boundary between the Ligure-Piemontese oceanic basin and the thinned Adria margin (Figure 7).

5.3. A Palaeotectonic Reconstruction of the Ligure-Piemontese Basin Configuration at the Dawn of Subduction

The presented stratigraphic and sedimentological features of the deposits associated with the Campanian-Maastrichtian coarse-grained debris found into the IL and western EL successions confirm the location of the double-vergent wedge closer to the Adria thinned margin than to the paired European continental margin, or in an intraoceanic setting. These characteristics therefore offer the possibility of deriving a likely configuration of the Ligure-Piemontese basin at the onset of convergence and subduction (Figure 7). As extensively described in the previous sections, the IL turbiditic formations are considered as representative of a complex turbiditic fan developed in the wide area connecting the Corsica-Europe continental margin and the deep-sea plain of the Ligure-Piemontese lower plate that was progressively involved into subduction. The Monte Gottero Sandstone Formation records this progressive interaction of the fan with the trench sedimentation system, as demonstrated by the transition from a feeding source represented only by the European-Corsican continental margin (Valloni & Zuffa, 1984), to a more proximal alimentation from the active prism, which provided the ophiolitic debris found in the upper part of the Monte Gottero Sandstone. These features are coherent with a wide basin located west of the Late Cretaceous accretionary wedge and capable of hosting the complex turbiditic fan as the one reconstructed for the IL succession (Figure 7). The coarse-grained debris of the Bocco Shale, stratigraphically tapering the Monte Gottero Sandstone and Zonati Shale, fits well in this picture, as representing gravity-driven deposits sliding from the prism slope onto the trench deposits and the subducting lower plate.

In contrast, the facies associations preserved in the western EL mélange are coherent with a deposition from tectonically triggered catastrophic and chaotic events in a narrow and confined basin (Figure 7). As reported, this small basin is thought to be bounded by two, well-defined morphotectonic structures: the retrowedge on the west and, on the east, the continental ribbon defined by Marroni et al. (2010), separating the western EL sedimentary basin from the basin of deposition of the eastern EL successions. Marroni et al. (2001) have depicted this continental ribbon as an inheritance of the rifting and spreading phases, that is, as a broader extensional allochthons made up of continental crust. A possible interpretation of this allochthons as the southernmost edge of the continental allochthons today represented by the Sesia-Dent Blanches nappes of the Western Alps (e.g., Beltrando et al., 2014; Manzotti et al., 2014) can be proposed. A Ligure-Piemontese domain bounded eastward by a continental domain is generally depicted in most pre-Campanian palaeogeographic reconstructions: to the south, this continental element is ascribed to the so-called AlKaPeCa microplate of Michard et al. (2002) and Guerrera et al. (2005). This domain (Figure 8), originally located south of Iberia-Europe plate, is thought to have been subsequently dismembered into several blocks (Alboran-Kabylies-Peloritan-Calabria) during the Oligo-Miocene tectonic evolution (e.g., Michard et al., 2002). The palaeogeographical location of the AlKaPeCa microplate strictly corresponds to the continental ribbon described by Marroni et al. (2001). Thus, a connection between the AlKaPeCa microplate and this continental ribbon can be also proposed (Figure 8).

In summary, Late Cretaceous subduction began on a western Tethys paleogeographic framework characterized by two main basins: (i) a westward basin represented by the Ligure-Piemontese basin that can be regarded as an oceanic strip located between the Europe passive margin (including Corsica, Sardinia and Iberia) and a continental ribbon and (ii) an eastward, wide basin with very thinned continental crust extending between the continental ribbon and the Adria margin (Figures 7 and 8). The evidence presented in this paper suggests that the initiation of subduction was located close to the thinned Adria margin, in the ocean-continent boundary zone, rather than in intraoceanic setting.

5.4. Buoyancy Analyses and the Initiation of Subduction: Applications to the Proposed Northern Apennines Evolution

It is widely accepted that subduction is triggered by gravitational instability and, consequently, that the most likely place for subduction to initiate is on oceanic lithosphere. In fact, oceanic lithosphere is universally considered as negatively buoyant beyond an age of ~30 Ma (e.g., Stüwe, 2007) and able to sink when a trigger is activated. Cloos (1993) has calculated that even oceanic crust as young as circa 10 Ma can be naturally susceptible to subduction and that subduction-related metamorphism can contribute by making prone to subduction even much younger lithosphere. In contrast, thermally stabilized continental lithosphere is much more buoyant, due to the presence of granitic crust with mean temperature, much higher than that of the underlying lithospheric mantle (Cloos, 1993).

The regions with thin continental crust and thick mantle lithosphere may be considered, as a whole, as negatively buoyant, and, according to McKenzie (1977), the transitional area between oceans and continents is a setting where these features are met. Then, modeling predicts that if forces are large enough, subduction can initiate at the boundary zone between oceanic and continental margins. In particular, processes of subduction initiation at an OCTZ have been studied using laboratory experiments (Goren et al., 2008; Mart et al., 2005) and numerical calculations (Nikolaeva et al., 2010). On the basis of the results of analog experiments, the authors suggested that the key factor for subduction initiation is a chemical density contrast between continental and oceanic lithospheres. Mart et al. (2005) proposed that the tendency of less dense material to "float" and of dense material to "sink" is the mechanism to produce to the development of reverse (inclined continentward) shear zone, thus breaking the lithosphere and inducing the subduction initiation. Also, Levy and Jupart (2012) have shown that continental extension at a passive margin can induce flexure of the oceanic plate. In addition, Nikolaeva et al. (2010) have calculated that subduction can start at an OCTZ when the negative buoyancy of the oceanic plate is achieved (already from 20 Ma old plate), and when the continental lithospheric mantle is rather depleted. Based on the evidence presented in this contribution, these requirements seem to be all satisfied by the transitional area between the oceanic plate and the Adria passive margin. First of all, the Ligure-Piemontese oceanic crust was old enough, more than 70–80 Ma, when the subduction started. Such an oceanic crust possesses a high average density and a large elastic thickness with respect to continental crust that can facilitate subduction initiation. Second, at the end of the rifting stage, in the lowermost Middle Jurassic, the Adria continental margin was shaped with an extremely thinned granitic crust underlain by a thick lithospheric mantle. Moreover, we have also shown that the large area of exhumed mantle in the OCTZ was characterized by depleted lherzolites, thus contributing to increase the buoyancy of the continental lithospheric column and matching the conditions expected in the modeling of Nikolaeva et al. (2010). We then suggest that the negative buoyancy of the 70–80 Ma old Ligure-Piemontese oceanic lithosphere strongly contrasted with the isostatic conditions of the thinned continental margin of the Adriatic plate, thus making the boundary zone between the oceanic plate and the thinned Adria continental margin a weak zone that could facilitate the onset of Late Cretaceous subduction, with respect to an intraoceanic setting (Figure 9a). Accordingly, ongoing subduction involved oceanic lithosphere in proximity of the thinned Adria margin and, occasionally, incorporated extensional allochthons, whose remnants are now preserved in the high-grade units of Alpine Corsica, and in the debris deposits of the forewedge and retro-wedge basins now represented by the successions of the Ligurian Units.

We can then postulate that the site of subduction initiation was inherited by the complex Jurassic evolution from thinning to breakup of the continental crust that lead to a detachment fault dipping below the European continental margin and a wide OCTZ toward the Adria lower plate (Marroni et al., 1998; Marroni & Pandolfi, 2007), similarly to what observed and modeled by Manatschal (2004) in exhumed structures in the Alps and in those active off the Iberia margin. Manatschal (2004) has proposed a model of architecture of OCTZ in magma-poor rifted margins in which the progressive thinning of the lithosphere until the continental breakup is characterized by a changing mode of deformation from overall pure shear, to localized simple shear deformation. Deformation occurs through development of several fault systems, comprising faults cutting solely across the brittle upper crust and soling out at middle to lower crustal levels, as well as faults with large amounts of extension down to deeper crustal levels, and responsible for exhumation of mantle rocks. In particular, the study reveals how the early stages of rifting are dominated by large extension, continentward dipping detatchment faults (see Figures 3c, 6, and 7 of Manatschal, 2004) active until the later stages of rifting and spreading, as shown in the profiles off Iberia margin (reflector C of Manatschal, 2004) and in the exhumed Pogallo fault and Margna fault of the Alps. Following this model, we propose that similar lithospheric shear zones dipping toward the Adria continent possibly represented weak sites to be reactivated during convergence, thus facilitating the inception of subduction in the Northern Apennine, at the boundary between the Ligure-Piemontese basin and the Adria thinned margin.

5.5. A Model of Late Cretaceous Subduction Initiation

The data and concepts discussed in the previous sections on the configuration of the Ligure-Piemontese basin and its transitions to the European and Adrian continental margins, and on the possible location of the Santonian-Campanian accretionary prism, can be integrated into an evolutionary model of subduction initiation that was influenced by the structures inherited from rifting and that, in turn, exerted a control on the following geodynamic evolution of the Northern Apennines (Figures 8 and 9).

Late Cretaceous convergence affected the Ligure-Piemontese basin bounded to the west by the transition to the Europe/Corsica passive margin, and to the east by an articulated OCTZ connecting the oceanic basin and the Adria thinned margin, characterized by extensional allochthons of different sizes, and by the exposure of subcontinental mantle (Figures 2c and 7). The configuration of the Adria side of the Ligure-Piemontese domain illustrated in Figure 7 shows a fragment of continental crust, possibly correlated with the Alpine Sesia-Dent Blanc nappe (Figure 8), separating two depositional basins in the thinned and stretched OCTZ.

The oldest evidence of subduction-related deformation and metamorphism dates back to circa 80 Ma and is recorded in slide blocks of continental affinity. The only estimate for the age of the deformation phases recorded by the IL successions comes from indirect observations (di Biase et al., 1997) and is ascribable to the Eocene-early Oligocene boundary. Therefore, the east dipping subduction and progressive closure of the Ligure-Piemontese basin initiated in the proximity of the OCTZ and involved pieces of continental crust and subcontinental mantle rocks from extensional allochthons since the beginning of the process, at 80 Ma (Campanian, Figure 9). Continued subduction determined the building of a double-vergent accretionary wedge that thickened by incorporation of pieces oceanic crust and its sedimentary cover, and of fragments of the thinned Adria margin. Prism growth from both sides caused the development of trench and retro-wedge sedimentation basins, both alimented by the prism slopes that provided debris of oceanic and continental affinity, all preserving a previous tectonometamorphic history of subduction and accretion (Figures 7 and 9).

The protracted subduction allowed the progressive involvement of the thinned continental crust of the Europe margin (Figure 9). In the middle Eocene, by the time the unthinned Europe continental crust arrives at the subduction zone, the Ligure-Piemontese was completely closed. During this event (Figure 9) the continental ribbon, whose remnants can be probably identified in the continental units of the Nebbio area (Corsica), was deformed and dismembered (Molli & Malavieille, 2011). However, the continuous convergence between the Europe and Adria margins continued well after this event (e.g., Schmid et al., 2017) and induced the deformation to be transferred toward the eastern EL basin. Until this time, the location of the subduction at the boundary between the Ligure-Piemontese oceanic basin and the OCTZ at the Adria margin allowed this basin to remain unaffected by convergence and shortening. According to the literature (Handy et al., 2010; Molli & Malavieille, 2011), this basin can be regarded as the weaker domain at this time, being characterized by subcontinental mantle covered by a very thinned continental crust along the Corsica-Adria transect, whereas to the south this basin became wider and floored by oceanic crust (Figure 8). We suggest that these conditions may have promoted the development of a new Apenninic subduction zone east of preexisting alpine subduction zone. Mantle lithosphere delamination and negative buoyancy of the still open eastern EL basin with respect to the unthinned Adria continental margin induced a change in subduction polarity, from eastward to westward, probably in late Eocene/early Oligocene time span (Marroni et al., 2010; Molli & Malavieille, 2011; Schmid et al., 2017). This new, Apenninic subduction evolved after cessation of the Alpine one and was coeval with the opening at 30 Ma of the Liguro-Provençal back-arc basin, as a consequence of the rotation of the Corsica-Sardinia rifted off the Provence margin of southern France (e.g., Gueguen et al., 1998). The new subduction system probably developed with a roughly N-S direction and produced the tectonic inversion of the Adria continental margin, which played the role of the upper plate during the Alpine subduction, and subsequently, represented the lower plate during the Apenninic subduction, and was affected by east verging shortening. As a consequence, the eastern EL basin was progressively shortened, whereas the former alpine building was heavily reworked. In particular, the eastern sector of the alpine wedge (i.e., the already deformed IL Units, western EL Units, and Schistes Lustrès Complex) was back thrusted onto the Adria continental margin (see Figure 1). Finally, the stretching of the whole system during the Mio-Pliocene ended up to the actual Apennines orogenic configuration (Figures 1 and 9).

6. Conclusions

1. The Campanian evolution of the Northern Apennines is characterized by an active double-vergent accretionary prism that separated two depositional basins: (1) the trench system and its transition to the Ligure-Piemontese oceanic basin, both representing the basin of formation of the IL successions and (2) a retrowedge basin hosting the deposition of the successions of the western EL mélanges.
2. Both basins were supplied by prism-derived debris including huge slide blocks with oceanic origin, as well as blocks derived from both continental crustal and subcontinental mantle.
3. Subduction involved rocks of the Ligure-Piemontese ocean and extentional allochthons from the Adria thinned margin since the beginning; therefore, it initiated at 80 Ma at the ocean-continent boundary zone.
4. The specific location of subduction inception, inherited from the rifting and the oceanic opening phases, might have influenced all the subsequent geodynamic evolution of the Apenninic orogeny from the flip of subduction polarity to the collisional stages.

Acknowledgments
This research was supported by funds "ATENEO grant" by Pisa University and MIUR PRIN project. We thank the Editor, John Geissman, and the Associate Editor, Meghan Miller, together with Gianni Capponi and an anonymous reviewer, for the constructive and detailed comments on the manuscript. We also thank the Guest Editors of the Special Issue "Orogenic cycles: from field observations to global geodynamics" (Virginia Toy, Gianreto Manatschal, Gideon Rosembaum, Megan Miller, and Rodolfo Carosi) for accepting publishing this contribution in the issue in commemoration of our colleague Marco Beltrando. The authors will be indefinitely thankful to Piero Elter for his inspiring view on the Northern Apennines geology. The data supporting the conclusions presented in this paper can be obtained by accessing the cited literature or by contacting the corresponding author.

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